PERFORMANCE OF PRE-CRACKED RC BEAMS SHEAR STRENGTHENED WITH NSM CFRP LAMINATES

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Abstract

The strengthening of an existing Reinforced Concrete (RC) structure often involves concrete in a cracked state. To evaluate the effect of existing cracks on the behavior of RC beams shear strengthened according to the Near Surface Mounted (NSM) technique with Carbon Fiber Reinforced Polymer (CFRP) laminates, an experimental program was carried. NSM CFRP laminates were applied in RC beams with or without cracks prior the application of the shear strengthening intervention. The main results of this experimental research are presented and analyzed in terms of the structural behavior of the beams, failure modes and effectiveness of the NSM technique with CFRP laminates. The principal difference of the behavior of NSM CFRP beams with and without pre-cracks can be resumed to an expected loss of initial stiffness in the pre-cracked specimens. However, the pre-cracking did not affect the efficacy of the NSM shear strengthening technique in terms of load carrying capacity and ultimate deflection.

Keywords: CFRP laminates, NSM, Pre-cracking, RC beams, Shear strengthening.

1. Introduction

A RC beam needs to be shear strengthened when is deficiently reinforced in shear or when its shear capacity falls below its flexural capacity after flexural strengthening. The shear failure mode of a RC beam should be avoided since it is brittle and unpredictable. Advanced composite materials like CFRP laminates applied according to NSM technique can be used in order to increase the shear resistance of RC beams [1-3]. This technique is based on the introduction of laminates into slits made on the concrete cover of the lateral faces of the beams to be strengthened. The strengthening intervention often involves concrete elements already cracked. To evaluate the influence, on the strengthening effectiveness, of already existing cracks when a RC beam is shear strengthened with NSM CFRP laminates an experimental program was carried out. The relevant results are presented and analyzed.

2. Experimental program

Fig. 1 presents the T cross section of the RC beams adopted in the experimental program, the lateral geometry of the type of beam and the steel reinforcement common to all tested beams (nine). The reinforcement systems were designed in order that all beams fail in shear. The differences between the tested beams are restricted to the shear reinforcement systems applied in the L_i beam span and the presence, or not, of the pre-cracks in the concrete before the application of the CFRP. The experimental program was made up of four beams with steel stirrups ϕ6@300mm (ρ_{sw} = 0.10%) and five beams with steel stirrups ϕ6@200mm (ρ_{sw} = 0.16%). According to Table 1, one NSM CFRP shear strengthening configuration (five laminates at 45º) was applied in three beams with ρ_{sw} = 0.10% (beams 3S-5LI45, 3S-5LI45F1 and 3S-5LI45F2) and in two beams with ρ_{sw} = 0.16% (beams 5S-5LI45 and 5S-5LI45F). In the beams 5S-5LI60 and 5S-5LI60F, both with ρ_{sw} = 0.16%, it was applied five NSM CFRP laminates at 60º. The 3S-5LI45F1, 3S-5LI45F2, 5S-5LI45F and 5S-5LI60F beams were pre-cracked before have been strengthened. As schematically represented in Fig. 1, the laminates were distributed along the AB line, where A represents the beam's support at its "test side" and B is obtained assuming load degradation at 45º.

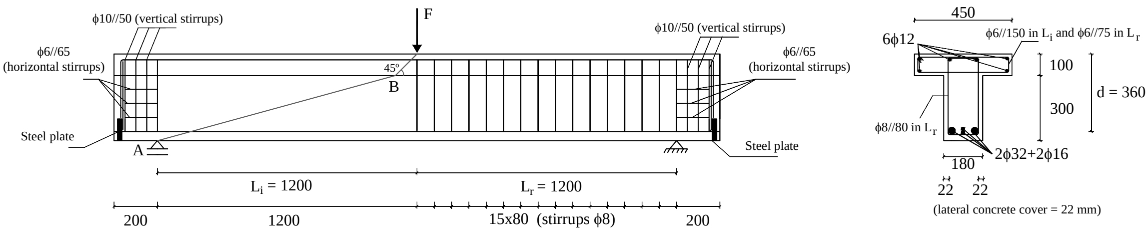


Fig. 1 - Geometry of the type of beam, steel reinforcements common to all beams, support and load conditions (dimensions in mm).

Table 1. CFRP shear strengthening configurations of the tested beams.

Beams	ρ_{sw} (%) [a]	Pre-cracking	Laminates	CFRP angle [θ_f] (º) [b]	CFRP spacing [s_f] (mm)	CFRP percentage [ρ_f] (%) [c]
3S-5LI45	0.10	No	2×5	45	275	0.08
3S-5LI45F1	0.10	Yes				
3S-5LI45F2	0.10	Yes				
5S-5LI45	0.16	No				
5S-5LI45F	0.16	Yes				
5S-5LI60	0.16	No		60	243	0.07
5S-5LI60F	0.16	Yes				

[a] 3S-R is the reference beam without CFRP for the beams with ρ_{sw} = 0.10% (Fig. 2) and 5S-R is the reference beam without CFRP for the beams with ρ_{sw} = 0.16% (Fig. 2); [b] Angle between the CFRP fiber direction and the beam axis; [c] The CFRP percentage was obtained from $\rho_f = (2a_f b_f)/(b_w s_f \sin\theta_f)$ where a_f = 1.4 mm and b_f = 9.5 mm are the dimensions of the laminate cross section, and b_w = 180 mm is the beam web width.

The three point beam bending tests (Fig. 1) were carried out using a servo closed-loop control equipment, taking the signal read in the displacement transducer (LVDT), placed at the loaded section, to control the test at a deflection rate of 0.01 mm/second. To prevent brittle spalling of the concrete cover at the supports, the beam ends were strengthened by confining the concrete with a two-directional cage of ϕ6@65mm horizontal stirrups and ϕ10@50mm vertical stirrups (Fig. 1). To overcome the difficulties to bend ϕ32 mm longitudinal tensile bars, their ends were welded to steel plates.

With the purpose of obtaining the strain variation along the three laminates (CFRP A, CFRP B and CFRP C) that have the highest probability of providing the largest contribution for the shear strengthening of the RC beam, strain gauges (SG_L) were bonded in these laminates according to the arrangements represented in Table 2. The localization of the SG_L in the pre-cracked beams was governed by the crack pattern formed at the end of the pre-cracking test. Therefore, in order to obtain the maximum strain values, strain gauges were positioned in the interceptions with the shear cracks. In each of the tested beam, one steel stirrup was monitored with three strain gauges (SG_S). The location of the monitored laminates and stirrups in the tested beams is represented in Fig. 2.

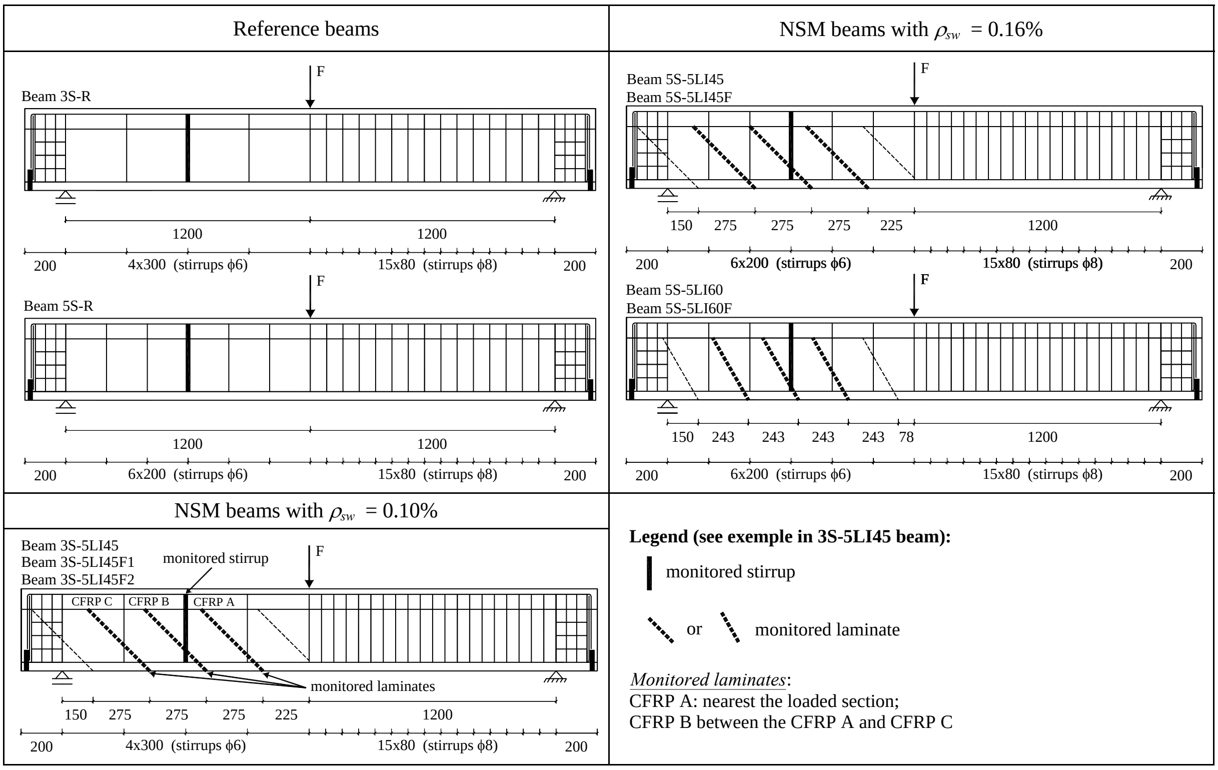
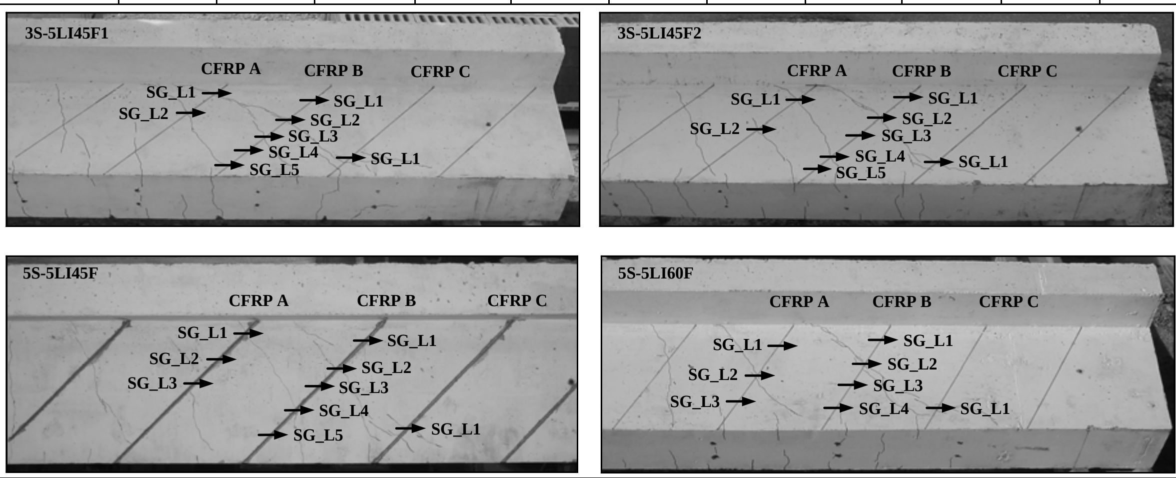


Fig. 2 - Localization of the steel stirrups (continuous line) and CFRP laminates (dashed line) in the tested beams (dimensions in mm).

Table 2 - Position of the strain gauges in the monitored CFRP laminates.

Beams	Position of the strain gauges in the monitored laminates [a]										
	CFRP A			CFRP B					CFRP C		
	SG_L1	SG_L2	SG_L3	SG_L1	SG_L2	SG_L3	SG_L4	SG_L5	SG_L1	SG_L2	SG_L3
3S-5LI45	7.1	21.2	35.3	8.5	17.0	25.4	33.9	-	7.1	21.2	35.3
3S-5LI45F1	5.3	14.5	-	8.7	17.5	25.4	31.9	38.3	36.5	-	-
3S-5LI45F2	6.9	20.1	-	7.4	14.8	23.4	31.9	37.2	33.8	-	-
5S-5LI45	7.1	21.2	35.3	8.5	17.0	25.4	33.9	-	7.1	21.2	35.3
5S-5LI45F	3.7	12.1	20.5	7.3	14.6	20.7	26.8	34.6	33.7	-	-
5S-5LI60	5.8	17.3	28.8	6.9	13.8	20.8	27.7	-	5.8	17.3	28.8
5S-5LI60F	8.8	17.6	26.1	7.0	14.0	20.8	27.5	-	28.6	-	-



[a] For each monitored laminate the value in this table refers to the length (in centimeters) of the laminate that is counted from the top the web beam to the position of the SG. For the beams without pre-cracks the spacing between SG´s is: L/3 (CFRP A and B) and L/5 (CFRP B) where L is length (in centimeters) of the laminate.

The concrete compressive strength at the date of beam testing was evaluated from uniaxial compression tests with cylinders (150 mm diameter and 300 mm height) according to EN 206-1 [4], and the average value obtained was 59.4 MPa. The properties of the steel bars (Table 3) were obtained from uniaxial tensile tests, carried out according to EN 10002-1 [5]. For the laminates (S&P Laminates CFK 150/2000), uniaxial tensile tests were carried out according to the ISO 527-5 recommendations [6], from which the following average values were obtained: maximum tensile strength = 2847.9 MPa, Young's modulus = 174300 MPa, ultimate tensile strain = 1.63%. The MBrace Resin 220 was used to bond the laminates to the concrete. This type of adhesive was tested by Bonaldo *et al.* [7] and the average values obtained in terms of maximum tensile strength, Young's modulus and ultimate tensile strain were 33 MPa, 7470 MPa and 4.83%, respectively.

Table 3 - Properties of the steel bars (average values).

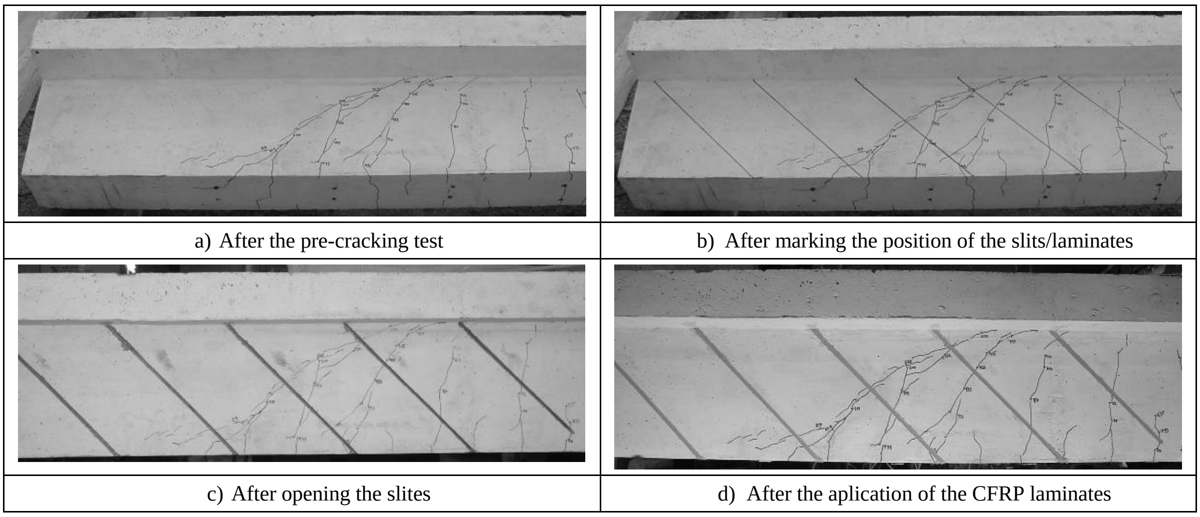
Property	ϕ6	ϕ8	ϕ12	ϕ16 (type 1)	ϕ16 (type 2)	ϕ32
Yield stress (MPa)	551	470	450	434	544	716
Tensile strength (MPa)	602	611	579	572	658	908

3. Experimental program

3.1 Pre-cracking test

As already mentioned, prior to the application of the NSM CFRP laminates, four RC beams (3S-5LI45F1, 3S-5LI45F2, 5S-5LI45F and 5S-5LI60F) were loaded up to a shear crack pattern was formed. For this purpose, and taking into account the behavior of the 3S-R and 5S-R reference beams (these beams were previously tested up to failure), a test stop criterion of a deflection of 3 mm at the loaded section was adopted. This value is about 30% of the deflection corresponding to *l/250*, which is the maximum allowed deflection for serviceability limit states according to the Eurocode [8], where *l* is the beam span length.

Considering the above mentioned stop criterion, the maximum load applied in the pre-cracking test was 239.9 kN, 232.6 kN, 245.4 kN and 253.4 kN for the 3S-5LI45F1, 3S-5LI45F2, 5S-5LI45F and 5S-5LI60F beams, respectively.



a) After the pre-cracking test
b) After marking the position of the slits/laminates
c) After opening the slites
d) After the aplication of the CFRP laminates

Fig. 3 - Strengthening activities after the pre-cracking test.

After the pre-cracking test, the strengthening activities were executed with the beams in the unloaded state (Fig. 3). In Fig. 4 are shown the cracking pattern of the beams after the pre-cracking test, and the adopted NSM CFRP shear strengthened configurations. The differences between 3S-5LI45F1 and 3S-5LI45F2 beams are restricted to the number of laminates crossing the shear crack formed during the pre-cracking test (three in 3S-5LI45F1 beam and two in 3S-5LI45F2 beam).

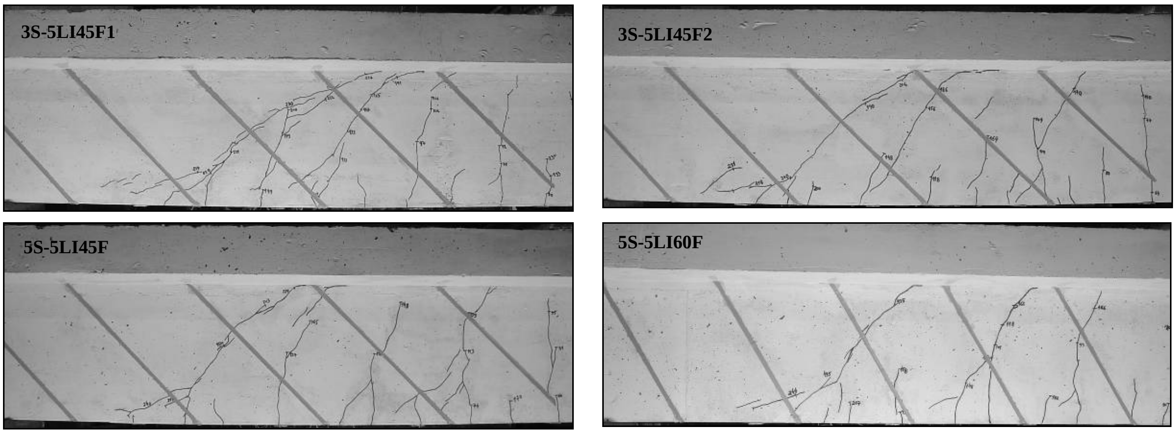


Fig. 4 - Pre-cracked RC beams shear strengthened with NSM CFRP laminates.

3.2 Test up to failure

The force-displacement diagrams (F-u) in the loaded section obtained for the tested beams are reported in Fig. 5. Assuming that $\Delta F_{max} = F_{max} - F_{max}^{ref}$, being F_{max}^{ref} and F_{max} the maximum force of the reference beam (3S-R or 5S-R) and of the shear strengthened beam, respectively, the $\Delta F_{max} / F_{max}^{ref}$ ratio was evaluated. The values for F_{max}, $\Delta F_{max} / F_{max}^{ref}$, and the deflection at loaded section corresponding to F_{max} ($u_{F_{max}}$) are included in Table 4.

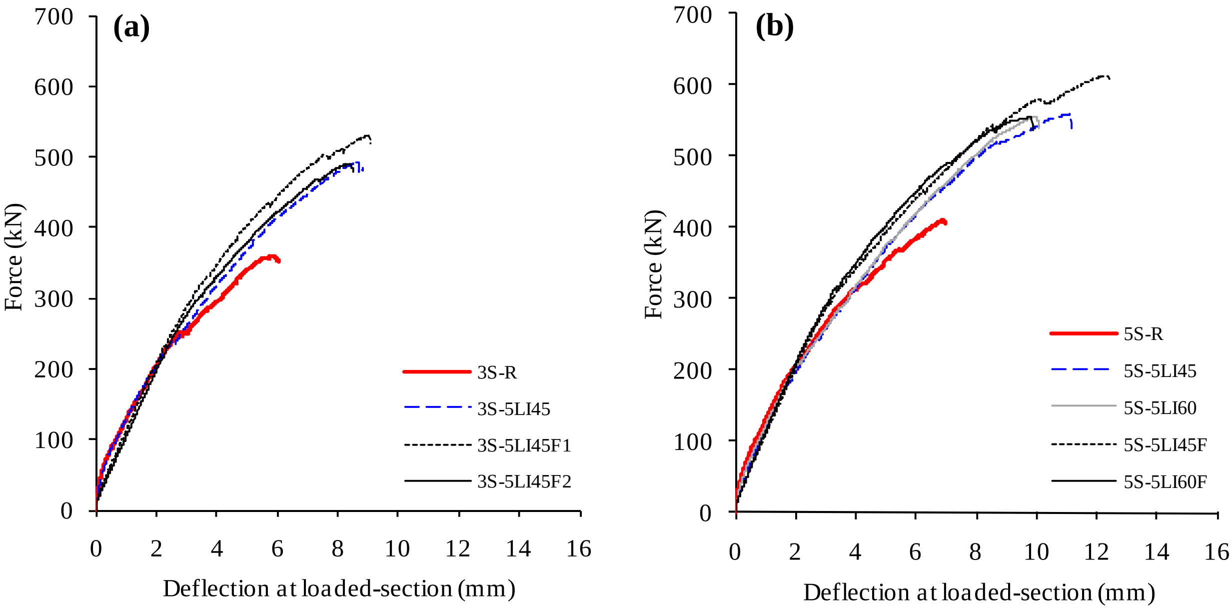


Fig. 5 - Force *vs* deflection at the loaded-section for the tested beams with the lower (a) and higher (b) percentage of steel stirrups.

Table 4 - Relevant results.

Beams	F_{max} (kN)	$\Delta F_{max} / F_{max}^{ref}$ (%)	$u_{F_{max}}$ (mm)	ε_{CFRP}^{max} (%)
3S-R	359.9	-	5.86	-
3S-5LI45	492.1	36.7	8.54	1.20
3S-5LI45F1	531.4	47.7	9.00	1.49
3S-5LI45F2	490.6	36.3	8.36	1.35
5S-R	409.7	-	6.86	-
5S-5LI45	559.5	36.6	11.09	1.28
5S-5LI45F	611.9	49.4	12.18	1.54
5S-5LI60	556.4	35.8	9.98	1.41
5S-5LI60F	554.8	35.4	9.73	1.48

Fig. 5 shows that the adopted NSM CFRP shear strengthening configurations provided an increase in terms of stiffness and in terms of maximum load (between 35% and 49%). Furthermore, the NSM CFRP shear strengthening configurations provided an increase in terms of deflection at the loaded section in correspondence to F_{max} ($u_{F_{max}}$) that ranged between 42% and 78%.

The main difference between the behavior of strengthened beams with or without pre-cracks resides in an expected loss of initial stiffness in the pre-cracked specimens (up to the maximum load applied in the pre-cracking test). This difference was more evident in the beams with ρ_{sw} = 0.10%. Above the load corresponding to the end of the pre-cracking test, the structural performance of 3S-5LI45F1 and 5S-5LI45F beams was slightly higher than the respective beams without a pre-cracking test (3S-5LI45 and 5S-5LI45, respectively). The maximum load (F_{max}) of 3S-5LI45F2 and 5S-5LI60F beams had similar values to the respective uncracked strengthened beams (3S-5LI45 and 5S-5LI60, respectively). The better performance of the 3S-5LI45F1 beam when is compared with that of the 3S-5LI45F2 beam can be justified by the number of laminates crossing the shear failure crack (the same that was formed during the pre-cracking test). The obtained results showed that the efficacy of the NSM shear strengthening technique with CFRP laminates is not negatively affected by the presence of a crack pattern that may exists when a strengthening intervention is needed.

Table 4 also compares the values of the maximum strain recorded in the monitored laminates up to maximum load (ε_{CFRP}^{max}) in the beams with NSM CFRP laminates. The values of ε_{CFRP}^{max} has ranged between 1.20% (3S-5LI45 beam) and 1.54% (5S-5LI45F beam). These values correspond to 74% and 94% of the CFRP ultimate strain obtained in the uniaxial tensile tests of the laminates (ε_{fu} = 1.63%) and confirm the high level of mobilization of the CFRP in the tested beams.

A very important aspect of the effectiveness of the NSM shear strengthening technique with CFRP laminates, regarding the analyzed beams, is the capacity of this technique to mobilize the yield stress of the stirrups before the maximum load of the strengthened beams has been attained.

As expected, all tested beams failed in shear in the L_i shear span. For the reference beams (3S-R and 5S-R), the maximum load was attained when one stirrup crossing the shear failure crack has ruptured. Debond through the laminate-adhesive interface (laminate sliding) was the predominant failure mode of the tested beams. The failure of the 5S-5LI45F beam occurred with the rupture of the intermediate laminate.

4. Conclusions

The adopted NSM CFRP shear strengthening configurations (ρ_f = 0.07÷0.08%), applied in RC beams with an average concrete compressive strength of about 60 MPa, provided an average increase of the maximum load (F_{max}) and of the deflection at the loaded section in correspondence to F_{max} ($u_{F_{max}}$) equal to 40% and 53%, respectively.

Due to the relatively high-strength concrete used, the resistance to the concrete fracture propagation during the debond process of the laminates crossing the critical diagonal crack has contributed to significantly mobilize the tensile capacity of the CFRP laminates. In fact, the maximum strain recorded in the laminates up to the maximum load has ranged between 74% and 94% of the CFRP ultimate strain obtained in the uniaxial tensile tests of the laminates.

The main difference of the behavior of NSM CFRP beams with and without pre-cracks resides in an expected loss of initial stiffness in the pre-cracked beams. In these beams the mobilization of the CFRP laminates started just after the opening process of the pre-cracks, while the mobilization of the CFRP laminates in the non pre-cracked beams only occurred when the shear crack has formed. However, the pre-cracking did not affect the efficacy of the NSM shear strengthening technique in terms of load carrying capacity and ultimate deflection.

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6. References

[1] BARROS, J., DIAS, S., “Near surface mounted CFRP laminates for shear strengthening of concrete beams”, *Journal Cement & Concrete Composites*, Vol. 28, No. 3, March 2006, pp. 276-292.

[2] KOTYNIA, R., “Shear strengthening of RC beams without NSM CFRP laminates”, *8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-8)*, July 2007, 10 pp. (CD-ROM).

[3] EL-HACHA, R., WAGNER, M., “Shear Strengthening of Reinforced Concrete Beams using Near-Surface Mounted CFRP Strips”, *9th International Symposium on Fiber Reinforced Polymers Reinforcement for Concrete Structures (FRPRCS-9)*, July 2009, 4 pp. (CD-ROM).

[4] EN 206-1, “Concrete - Part 1: Specification, performance, production and conformity”, *European standard - CEN*, 2000, 69 pp.

[5] EN 10002-1, “Metallic materials - Tensile testing. Part 1: Method of test (at ambient temperature)”, *European standard - CEN*, 1990, 35 pp.

[6] ISO 527-5, “Plastics - Determination of tensile properties - Part 5: Test conditions for unidirectional fibre-reinforced plastic composites”, *International Organization for Standardization (ISO)*, 1997, 7 pp.

[7] BONALDO, E., BARROS, J., LOURENÇO, P., "Steel fibre reinforced concrete and CFRP laminate strips for high effective flexural strengthening of RC slabs", *Technical report 05-DEC/E-14 – Department of Civil Engineering, University of Minho*, October 2005, 103 pp.

[8] EN 1992-1-1, "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings", *European standard - CEN*, 2004, 225 pp.